

A 10,000 YEARS OLD EXPLOSION IN DR21

LUIS A. ZAPATA¹, JOHANNES SCHMID-BURCK², NADIA PÉREZ-GOYTIA¹, PAUL T. P. HO^{3,4},
 LUIS F. RODRÍGUEZ¹, LAURENT LOINARD¹, AND IRENE CRUZ-GONZÁLEZ⁵

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ABSTRACT

Sensitive high angular resolution ($\sim 2''$) CO(2-1) line observations made with the Submillimeter Array (SMA) of the flow emanating from the high-mass star forming region DR21 located in the Cygnus X molecular cloud are presented. These new interferometric observations indicate that this well known enigmatic outflow appears to have been produced by an explosive event that took place about 10,000 years ago, and that might be related with the disintegration of a massive stellar system, as the one that occurred in Orion BN/KL 500 years ago, but about 20 times more energetic. This result therefore argues in favor of the idea that the disintegration of young stellar systems perhaps is a frequent phenomenon present during the formation of the massive stars. However, many more theoretical and observational studies are still needed to confirm our hypothesis.

Subject headings: stars: pre-main sequence – ISM: jets and outflows – individual: (DR21) – individual: (DR21 Outflow)

1. INTRODUCTION

Located in the Cygnus X complex at a distance of 1.36 ± 0.12 kpc (Rygl et al. 2012), the outflow in DR21 is probably one of the most enigmatic high-velocity molecular outflows associated with star forming regions. This outflow is extremely massive ($> 3000 M_{\odot}$) and energetic ($> 10^{48}$ erg) with a luminosity in the $2 \mu\text{m}$ band alone calculated to be $1800 L_{\odot}$ (Garden et al. 1991; Garden & Carlstrom 1992). The DR21 outflow has been suggested to be energized by a massive protostar with bolometric luminosity of about $10^{5-6} L_{\odot}$ (Garden et al. 1991; Garden & Carlstrom 1992), which would exceed the total bolometric luminosity of DR21 region ($10^5 L_{\odot}$; Harvey et al. 1977). However, such a massive star has so far never been clearly found out (Cruz-González et al. 2007).

The outflow appears to be bipolar with its strongest molecular lobes extending northeast-southwest, and emanating from a dense dusty filament that extends from north to south (Schneider et al. 2010). However, there are some faint H₂ filaments that show different orientations with some of them pointing back to the DR21 main.

It has been suggested that the axis of this bipolar outflow might be located very close to the plane of the sky (e.g. Garden et al. 1991), however, the high velocity wings observed in H₂ and CO (-80.82 to $+46.84$ km s⁻¹) and the overlapping of blue/redshifted emission on both lobes (Cruz-González et al. 2007; Schneider et al. 2010) indicate a different scenario for its orientation. Commonly bipolar outflows with their axes located close to the plane of the sky show slow radial velocities with their blue/redshifted lobes well separated (e.g. Pech et al. 2012). However, overlapping blue/redshifted emission on both lobes might result from an outflow in the plane of the sky (that seems to be unlikely due

to its high velocity wings) if the outflow is thought of as a cone with one side of the cone coming toward us and the other side moving away.

Garden et al. (1991); Garden & Carlstrom (1992); Cyganowski et al. (2003); Davis et al. (2007) additionally reported the presence of some collimated flows emanating from DR21 with different orientations to the main NE-SW DR21 outflow.

In high-density protostar clusters, envelopes and disks provide a viscous medium that can dissipate the kinetic energy of passing stars, greatly enhancing the probability of capture. This process opens the possibility of having protostellar mergers that may generate impulsive wide-angle outflows, shock-induced masers, radio continuum emission, and runaway massive protostars. Both the ejection of massive stars and the launch of the impulsive outflow may be the result of the dynamic interaction and rearrangement of a system of massive stars. This process has been extensively discussed in Bally & Zinnecker (2005); Bally et al. (2011).

Very recent sensitive ¹²CO(2-1) millimeter and infrared observations have suggested that the massive ($10 M_{\odot}$) and energetic ($\sim 10^{47}$ erg) outflow located in the Orion BN/KL region appears to have been produced by such a violent explosion during the disruption of the massive young stellar system of which the infrared and radio sources *BN*, *n*, and *I* were all members about 500 years ago (Zapata et al. 2009, 2011a,b; Bally et al. 2011). This suggests that the complex of CO and H₂ emission in BN/KL is due to a phenomenon different from the well known collimated outflows produced by the young stars commonly associated with star formation. With this recent result in mind, one could consider if the flow emerging from DR21 could be a similar case as that occurred in BN/KL 500 years ago.

We thus here report new SMA interferometric observations of this outflow trying to elucidate its nature.

2. OBSERVATIONS

¹ Centro de Radioastronomía y Astrofísica, UNAM, Apdo. Postal 3-72 (Xangari), 58089 Morelia, Michoacán, México

² Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany

³ Academia Sinica Institute of Astronomy and Astrophysics, Taipei, Taiwan

⁴ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

⁵ Instituto de Astronomía, Universidad Nacional Autónoma de México, Ap. 70-264, 04510 DF, México

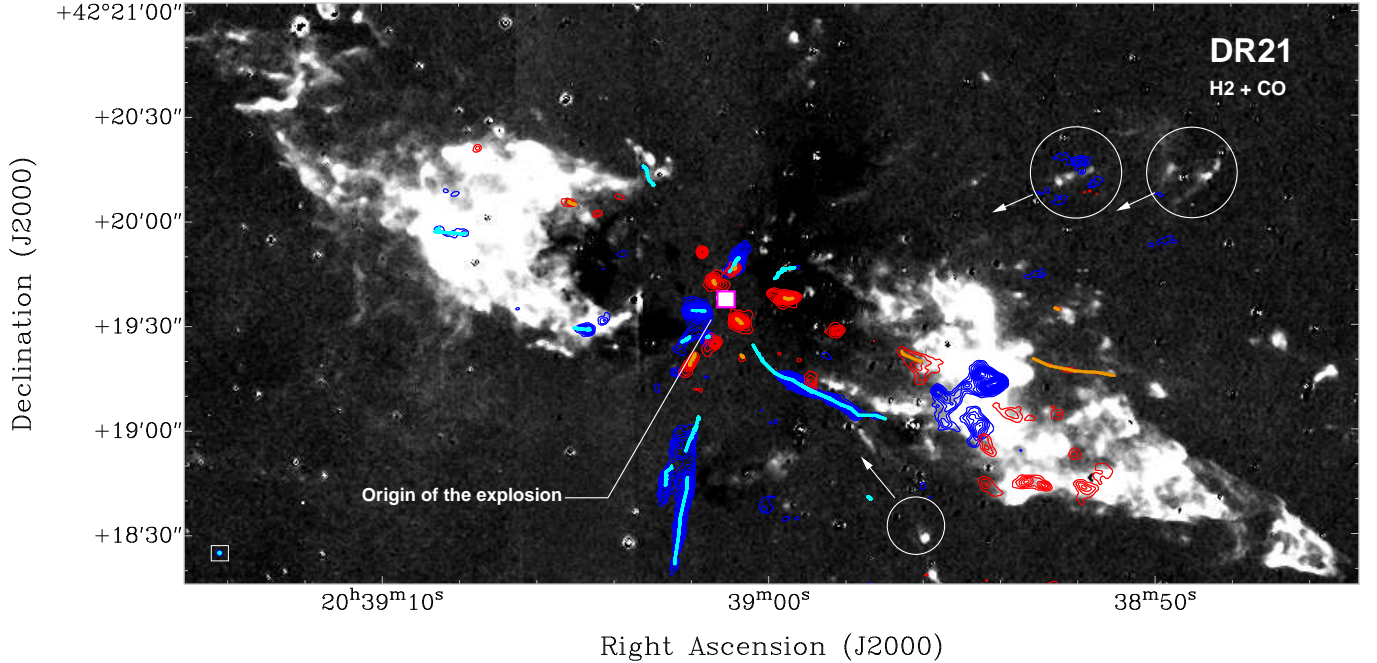


FIG. 1.— High velocity redshifted (red/brown) and blueshifted (blue) CO(2-1) filaments in the DR21 outflow as observed with the SMA, overlaid on an H₂ image from Davis et al. (2007). The blue contours are from 13% to 90% in steps of 3%, the peak of the molecular emission; the peak emission is 21 Jy beam⁻¹ km s⁻¹. The red contours are from 12% to 90% in steps of 5%, the peak of the molecular emission; the peak emission is 16 Jy beam⁻¹ km s⁻¹. Each line represents one sequence of positions at which the CO emission peaks in consistent velocity channels. Most of the filaments point approximately toward the same central position (represented here by a box) $\alpha=20^h 39^m 11.1^s \pm 5''$ and $\delta=+42^\circ 19' 37.9'' \pm 5''$. The size of the box represents the errors given in the text. There are also some H₂ faint filaments that appear to point toward the same central position (Davis et al. 2007). These H₂ filaments are marked with white circles. We used the mosaicing mode to cover the entire DR21 outflow as far as it has been mapped in H₂. The synthesized beam is shown in the lower left corner.

The observations were made with the Submillimeter Array⁶ (SMA) during 2011 August and 2012 July/August. The SMA was in its subcompact, compact, and extended configurations with baselines ranging in projected length from 7 to 160 m. We used the mosaicing mode with half-power point spacing between field centers and covered the entire DR21 outflow mapped in H₂ by Davis et al. (2007), see Figure 1. We concatenated the three data sets using the task in MIRIAD called “uvcat”. The three different observations were identical, and only the antenna configuration of the SMA changed.

The SMA correlator was configured in 24 spectral “chunks” (or windows) of 104 MHz each, with 128 channels distributed over each spectral window, providing a spectral resolution of 0.8125 MHz (1.05 km s⁻¹) per channel. The receivers were tuned to a frequency of 230.5387 GHz in the upper sideband (USB), while the lower sideband (LSB) was centered on 220.5387 GHz. The ¹²CO(2-1) transition was detected in the USB at frequencies close to a frequency of 230.5 GHz. The full bandwidth of the SMA correlator is 8 GHz (4 GHz in each band).

The zenith opacity ($\tau_{230\text{GHz}}$) was $\sim 0.1 - 0.3$, indicating reasonable weather conditions. Observations of Uranus provided the absolute scale for the flux density calibration. Phase and amplitude calibrators were the star MWC349a, and the quasar J2007+404. Further technical descriptions of the SMA and its calibration schemes can be found in Ho et al. (2004).

The data were calibrated using the IDL superset MIR, orig-

inally developed for the Owens Valley Radio Observatory (Scoville et al. 1993) and adapted for the SMA.⁷ The calibrated data were imaged and analyzed in a standard manner using the MIRIAD, and KARMA (Gooch 1996) packages. The line image rms noise was around 100 mJy beam⁻¹ for each velocity channel at an angular resolution of $2''.17 \times 1''.89$ with a P.A. = $+74.0^\circ$.

3. RESULTS AND DISCUSSION

In Figure 1, we show the ¹²CO(2-1) molecular emission detected in our SMA mosaic towards the DR21 region. We construct this large scale integrated intensity map only using the emission arising from the high velocity gas and thus avoiding the emission in the range from -15 to 15 km s⁻¹. In this velocity range the line emission is spatially extended, and could not be well sampled by the SMA. In our channel velocity maps, we found that the redshifted ¹²CO(2-1) emission shows radial velocities from $+3$ up to $+50$ km s⁻¹, while the blueshifted one from $+3$ down to -80 km s⁻¹. This velocity range is in very good agreement to that previously observed by Garden et al. (1991); Schneider et al. (2010). However, our high angular resolution observations revealed clear molecular filaments with different orientations, and some of them well correlated with H₂ emission (Figure 1).

The CO filaments reported here are composed of about three hundred compact features observed in our channel velocity cube with velocity windows of 1 km s⁻¹ and their positions on the sky are shown in our Figure 1. The observational parameters of these compact features were found us-

⁶ The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.

⁷ The MIR cookbook by C. Qi can be found at <http://cfa-www.harvard.edu/~cqi/mircook.html>

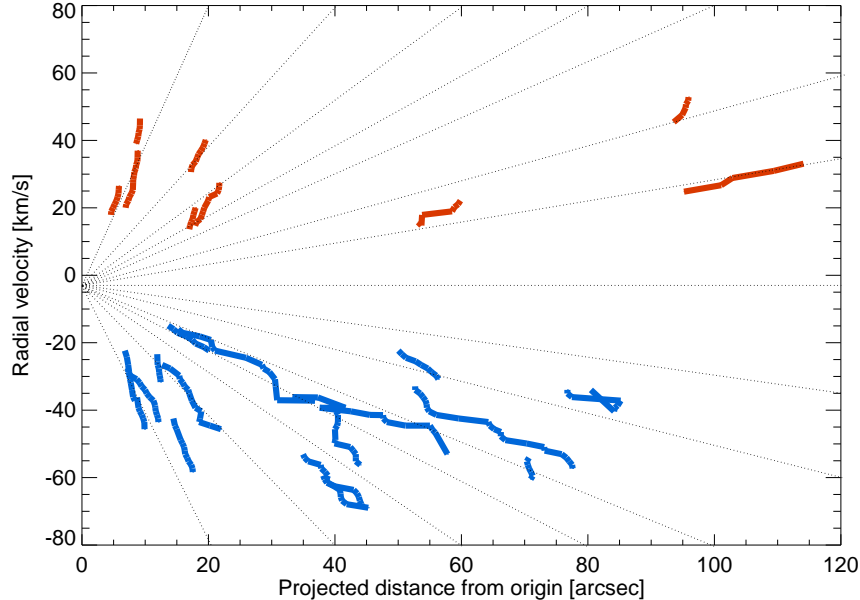


FIG. 2.— Position-velocity diagram of the jet-like CO complex: Radial velocity as function of on-the-sky distance from the common center for each of the 25 CO(2-1) filaments, with blueshifted structures shown in blue, and the redshifted ones in red. Nearly all filaments seem to start from the same common radial velocity of about -3 km s^{-1} (the small black circle). Black gradient dashed-lines start from -3.0 km s^{-1} . Note that velocities between -15 and $+15 \text{ km s}^{-1}$ could not be studied because the interferometer cannot sample well the extended molecular gas.

ing the task *imfit* of MIRIAD. Each of these filaments show clear velocity gradients that follow a Hubble law (Figure 2). Furthermore, most of these filaments appear to point out a common velocity center located at about -3.0 km s^{-1} , in very good agreement with the ambient molecular velocity of DR21 (-3.0 km s^{-1} ; Schneider et al. 2010).

Many of these physical features are also found in the molecular outflow located in BN/KL and are related to an explosive event occurred 500 years ago as described in the introduction. However, the outflow in DR21 has a clear east-west bipolar shape observed on the H_2 maps. This H_2 bipolar shape could be due to the highly extinction produced by the north-south dusty lane where many of the CO filaments are revealed for the first time. This also seems to be the case in the outflow located in BN/KL, see Zapata et al. (2011a).

Using a similar approach to that applied in Zapata et al. (2009), we determine the position of the origin of the CO filaments in $\alpha(\text{J2000})=20^{\text{h}} 39^{\text{m}} 1.1^{\text{s}} \pm 0.3^{\text{s}}$ and $\delta(2000)=+42^{\circ} 19' 37.9'' \pm 5''$.

This position coincides well with the center of an expanding cometary HII region (see Figure 3) imaged by Cyganowski et al. (2003). This positional coincidence suggests that both the explosive outflow and the large cometary HII region were probably produced by the same mechanism. Moreover, at the position of the outflow origin there is not a single young (radio, submillimeter, or infrared) star, suggesting that maybe its "source" is no longer located there, as in the case of the explosive outflow in Orion BN/KL (Zapata et al. 2009). There is also a depression of centimeter continuum emission at this position (see Figure 3).

The explosive Becklin-Neugebauer (BN)/Kleinman-Low (KL) outflow emerging from OMC1 behind the Orion Nebula was powered by the dynamical decay of a non-hierarchical multiple system ~ 500 years ago that ejected the massive stars I, BN, and source n, with velocities of about $10 - 30 \text{ km s}^{-1}$

(Zapata et al. 2009, 2011a,b; Bally et al. 2011). In this dynamical decay of a non-hierarchical multiple system a kinetic energy of about 10^{47} ergs was liberated.

If we assume that the outflow in DR21 was produced by a dynamical decay of a non-hierarchical multiple system, the kinetic energy liberated on that disruption was about 20 times larger than that in the Orion BN/KL system ($> 2 \times 10^{48}$ erg; Garden et al. 1991; Garden & Carlstrom 1992).

Again, very crudely assuming that the velocities of the stars ejected in DR21 have similar velocities as the ones located in Orion BN/KL (this without any evidence), and a dynamical age of about 10,000 years⁸ (obtained from our molecular data, $t_d \sim 1.2 \times 10^{18} \text{ cm} / 4 \times 10^6 \text{ cm s}^{-1} \sim 10,000 \text{ yrs}$) for the outflow in DR21. The reader should note that this estimation is also an approximation, since the values for the velocity are only radial velocities, and the displacements are only the projected components.

We thus found that the ejected stars should be located about $25''$ far from the center of the DR21 outflow. This is exactly the distance of the bright infrared source "DR21-D" associated with a small cometary HII region (Figure 3) with respect to the origin of the outflow in DR21. This suggests that maybe DR21-D is related with the explosive event in DR21. The Figure 3 also reveals a reflecting east-west cavity associated with the large cometary HII region. These infrared nebulosities are also observed in Orion BN/KL and most of them are not heated by stars. They are possibly heated by strong shocks produced by the explosive outflow (Menten & Reid 1995; Zapata et al. 2011a).

All the characteristics found in these observations in the outflow located in DR21 are very similar to the ones reported in the explosive outflow located in Orion BN/KL (Zapata et al. 2009). We thus propose that the complex of

⁸ This is an approximate 1st order estimation as in the case of the Orion BN/KL (Zapata et al. 2009)

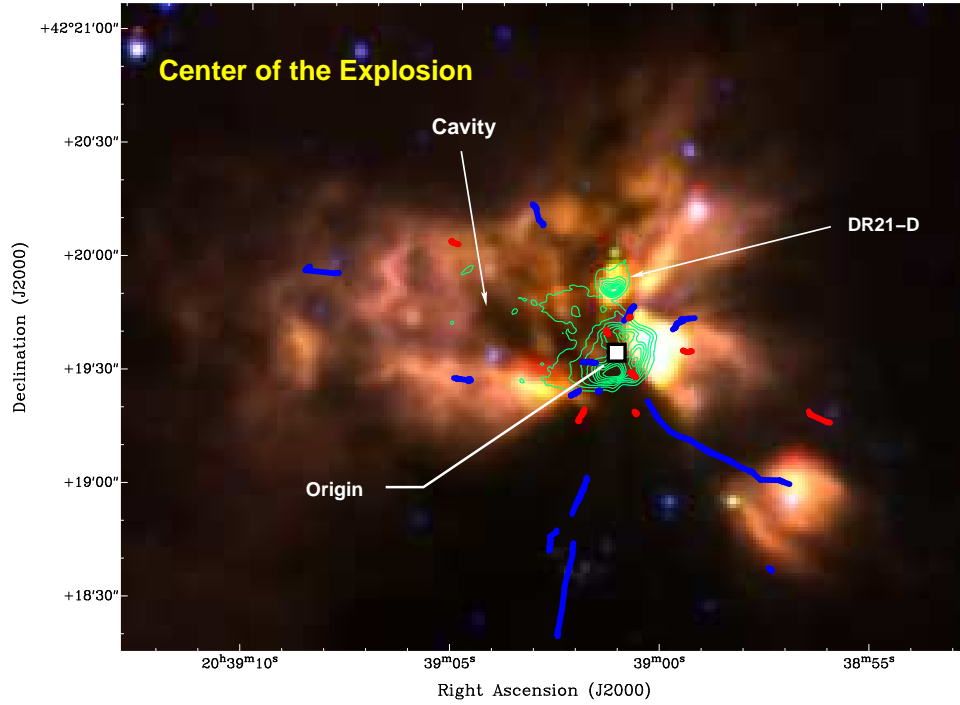


FIG. 3.— Redshifted and blueshifted CO filaments in the DR21 outflow as observed with the SMA, overlaid on a Spitzer infrared color image and a VLA 6 cm. emission contour image. In the Spitzer infrared color image composite the red represents the $8.0\ \mu\text{m}$, green the $5.8\ \mu\text{m}$, and blue the $3.6\ \mu\text{m}$ emission. The contours are 5% to 90% with steps of 10% the peak of the centimeter emission; The peak of the centimeter image is $0.13\ \text{Jy Beam}^{-1}$. The center of the explosive molecular outflow is marked with a white square. Note that this center coincides with the center of the compact HII region revealed by the 6.0 cm. continuum emission map. Additionally, the infrared map reveals a continuum source associated with the cometary HII region called DR21-D. Note that the white square does not lie at the peak of the 6.0 cm. emission, rather it is located in the middle of the HII region, where no emission is detected at all.

CO and H_2 emission located in DR21 might have been produced by an explosive phenomenon different from the standard disk-outflows associated with star formation. This outflow was probably originated during the disintegration of a massive stellar system as the one occurred in Orion BN-KL some 500 years ago. As mentioned in the Introduction section, the process of that disintegration of the stellar system has been discussed in detail by Bally & Zinnecker (2005). The presence of explosive phenomena in two of the best studied regions of massive star formation suggests that the phenomenon may be more common than previously thought and that future detailed studies may reveal more of them in other regions.

4. CONCLUSIONS

Sensitive high angular resolution ($\sim 2''$) CO(2-1) line observations made with the Submillimeter Array of the flow emanating from the massive star forming region DR21 located in the Cygnus X molecular cloud have been presented. We found about 25 molecular blueshifted and redshifted fila-

ments. These molecular filaments follow nearly straight lines and appear to all point toward a common center. The radial velocity along each filament follows clearly a Hubble law, indicative of an explosive event. Our observations suggest that this outflow appears to have been produced by a violent explosion that took place about 10,000 years ago, and that seems to be related with the disintegration of a massive non-hierarchical stellar system, as the one that occurred in Orion BN/KL, but about 20 times more energetic. However, many more theoretical and observational studies are still needed to confirm our hypothesis.

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